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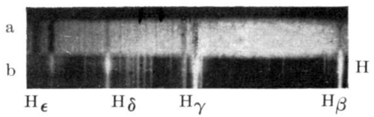

Fig. 2

a. Solar Spectrum
b. Hydrogen

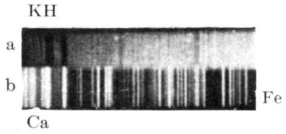

Fig. 3

a. Solar.
b. Fe and Ca.

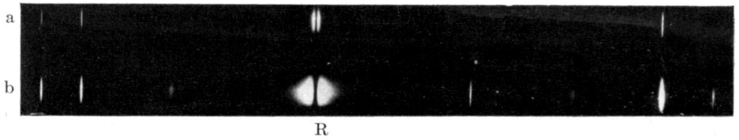

Fig. 4. Arc spectrum of barium

a. Small quantity in arc
b. Large quantity in arc
R. Self-reversal

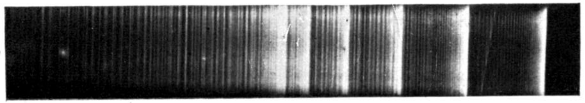

Fig. 5. Band spectrum, carbon arc

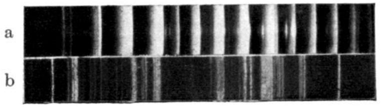

Fig. 6

Nitrogen

a. Band spectrum
b. Line spectrum

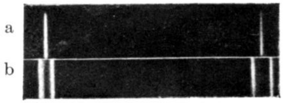

Fig. 7

Zeeman effect, Fe

a. No field
b. With field

PLATE IX

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THE SPECTROSCOPE, KEY TO CELESTIAL AND ATOMIC MYSTERIES[1]

BY E. P. LEWIS

About eighty years ago Auguste Comte, in his Positive Philosophy, made the statement that the chemical constitution and the physical state of the heavenly bodies must forever remain unknown to us. Less than twenty years later Kirchhoff and Bunsen established the principles of spectrum analysis and Huggins showed that with the spectroscope we can secure exact information as to the constitution of the stars. From that time to this there has been a steady accumulation of data which throw light not only on the chemical constitution, but also on the physical state and the velocities of heavenly bodies. In this work it is gratifying to know that the two great observatories of California have been leaders, and later in this course of lectures you will learn much of these results from those who have achieved them. Not only has the spectroscope made it possible for us to extend our observations to the remotest parts of the visible universe, but it has also done much to aid us in obtaining some idea of the minute details of atomic structure. The object of this lecture is to explain in the simplest terms the underlying principles of the spectroscope, to show you some experiments illustrating these principles and some photographs of typical spectra, and to give you some idea of the progress which has been made in learning some of the secrets of atomic structure.

The separation of white light into its constituent colors by transparent prismatic bodies must have been observed by the ancients, but Newton was apparently the first to study this phenomenon systematically, and to show that these colors could not be further decomposed by sending them thru another prism, while when recombined they again formed white light. Largely because of Newton's erroneous idea that light consists of small particles projected with great velocities from the source, no further advance was made for more than a century.

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[1] A lecture delivered in San Francisco on Friday evening, October 29, as the introductory one of the course of six popular lectures on phases of the new astronomy to be given this season under the auspices of the Astronomical Society of the Pacific. Laboratory apparatus was utilized to produce on the screen many of the spectra described. Lantern slides illustrations were also used.

Before describing the progress which has been made since the beginning of the nineteenth century, it may be well to describe the simple form of spectroscope which is built up on the table before you. (Fig. 1). A beam of light from an electric arc is focused by a lens on a narrow slit *S*, which is an essential part of every spectroscope. After passing thru the slit the light goes thru a second lens *L*, which will form an image of the slit at *I* on a screen at a certain distance. If the prism *P* is placed in the pencil of light, the latter will be refracted toward the base of the prism. The different colors will be bent thru different angles, so that the white light is spread out into a long band, called a spectrum, red at one end, violet at the other. If only three colors, definite shades of red, green and violet are present in the light, there will be three slit images in these colors at the points *R*, *G*, and *V*. These are called spectrum lines. This is the basic plan of all spectroscopes, altho they are usually of more complicated mechanical construction. Often the prism is replaced by a diffraction grating consisting of a polished glass or metal plate upon which many thousand close and equidistant lines have been ruled with a diamond point. These produce a number of spectra, due to the separation of different colors by interference between light waves of different lengths. Similar effects may be observed on looking at a distant electric light thru a fine meshed handkerchief. In many cases the eye is replaced by a camera, with which a permanent record of the spectrum may be photographed. In this case the instrument is called a spectrograph.

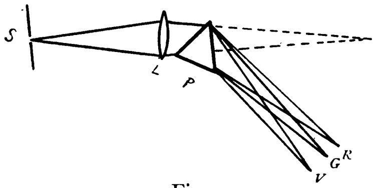

Fig. 1

If we use for a source a flame colored with any compound of sodium the spectrum will consist of two lines very close together in the yellow, each evidently an image of the slit. It is clear that there will be as many slit images, or spectrum lines, as there are colors in the light. The unbroken gradation of colors shown in the spectrum of a candle or of the white hot poles of the electric arc shows that their light consists practically of an infinite number of colors, gradually merging into each other, rather than the seven distinct colors specified by Newton. Such a spectrum is called continuous. You will note that the spectrum of the luminous vapors between the poles of the arc is not continuous, but shows the yellow lines of sodium and several broad bands which are due to carbon or carbon compounds, with dark spaces between them. It is generally true that luminous gases and vapors give such discontinuous spectra, or in other words they emit a finite number of colors.

In the year 1800 William Herschel made the first advance since the time of Newton. He discovered that beyond the red of the solar spectrum there is an intense invisible radiation. This "infra-red" region may be explored with various types of very sensitive thermometers. A little later Ritter discovered similar "ultra-violet" radiations, by the effect produced upon sensitive silver salts. The modern photographic plate is very sensitive to these rays. About the same time Thomas Young showed conclusively that light is due to wave motion. If a pebble is thrown into a smooth pond a circular ripple wave will proceed from it. If two pebbles are thrown in at different points, two sets of waves will be generated. Wherever the crest of one meets a crest of the other the displacement will be increased. Wherever a crest meets a hollow, the waves may neutralize each other completely by destructive interference. You can easily repeat Young's method of producing similar effects with light waves by ruling two fine slits very close together in the gelatine of a blackened photographic plate and looking thru them at the filament of a distant incandescent lamp. You will see a central image of the filament, with a series of narrow spectra on each side. Light of different wave-lengths and color will be reinforced or weakened at different points, so that the different colors are separated from each other. If we multiply the number of such openings, or reflecting grooves in a polished metal plate, we have a diffraction grating, with which measurements of wave-lengths may be easily and accurately made. The longest visible waves give rise to the sensation of red, and have a length of about one thirty-thousandth of an inch. The shortest are the violet, which have a wave-length somewhat more than half as great. Recently it has been shown that X-rays are due to waves of still shorter length, one-thousandth to one ten-thousandth as long as those mentioned above. Their spectra are produced by interference effects due to their reflection from a large number of equidistant atomic planes of crystals.

In 1814 Fraunhofer discovered that the solar spectrum is crossed by a large number of fine dark lines parallel to the slit of the spectroscope, two of which coincided with the bright lines of sodium. It is evident that each dark line indicates the absence of a corresponding slit image, and therefore of that particular color or wave-length in the light of the Sun. These Fraunhofer lines are illustrated by the photographs of the solar spectrum shown in Figs. 2 and 3, Plate IX, and on a much larger scale by the large map of the solar spectrum made by Professor Rowland with a powerful diffraction grating, on which many thousands of these lines appear. The significance of these lines was not apparent at the time. Meanwhile many investigators noted the different colors shown by flames containing salts of sodium, calcium, strontium and other elements, and found that their spectra showed characteristic differences. In 1849 it was noted by Foucault that the yellow lines emitted by a flame colored with sodium correspond exactly in position with two dark lines in the solar spectrum, and he succeeded in reproducing these lines in the continuous spectrum of the electric arc by an experiment which I shall now imitate. The spectrum of the arc is thrown on the screen. Above is the continuous spectrum of the carbon pole. Below it is the spectrum of the flame of the arc, in which the sodium lines are prominent, and are made more intense by the addition of common salt to the arc. Just in front of the slit I burn a piece of metallic sodium in an alcohol flame. As the yellow blaze rises across the slit and thru the beam of light from the arc, you see a broad dark line appear in the continuous spectrum of the latter just above the bright sodium lines. It is evident that the sodium vapor in the flame absorbs more of the yellow light coming from the hotter arc than it emits itself, so that this particular color is greatly weakened in the spectrum of the arc. The great significance of the different discontinuous spectra observed by various individuals, the Fraunhofer lines, and Foucault's experiment was first clearly realized by Kirchhoff and Bunsen in 1859, when they definitely established the conclusion that every luminous gas or vapor emits a limited number of colors, with a corresponding number of slit images, the number and positions of these lines being characteristic of the substance; and further, that in many cases, as in the phenomenon observed by Foucault, such vapors will absorb a large part of the light of the same wave-lengths as they emit if they are placed in the path of the light coming from a brighter source. The differences in the number and positions of the spectrum lines of different elements can be due only to differences in the size and structure of the atoms which are the sources of the light waves, hence it is apparent that there must be a close relation between spectra and atomic structure.

The explanation of the absorption of light causing the Fraunhofer lines was first suggested by Stokes, and was based upon an acoustical analogy. Here are two tuning forks of exactly the same pitch. If one is set into vibration it is found that in a few seconds the other will be vibrating vigorously. This is an example of the familiar phenomenon known as resonance. If I slightly change the period of vibration of one fork by loading it with a bit of soft wax it will no longer respond. The explanation may be made clear by a familiar analogy. The vibrations of a swing may be steadily increased in amplitude by giving it a push in the right direction at regular intervals corresponding to its natural period of vibration. In like manner the initial sound wave starts the second fork to vibrating, and if each succeeding wave arrives at the proper instant to give the fork an additional impulse in the right direction it will soon vibrate with great energy. This will not occur if the periods of the two forks are different, as the effect due to the first waves will soon be neutralized by succeeding waves in different phases. Light waves must be due to the vibrations of parts of atoms, and if all sodium atoms are precisely alike, their periods of vibration must be the same, and we should expect that sodium atoms placed in the path of light waves of the same frequency would have vibrations set up within them, so that some of the incident energy will be absorbed. Some of this is again radiated, but in all directions instead of pursuing the original direction of the incident light, so that there will be a reduction of intensity in that part of the spectrum corresponding to the colors absorbed.

Thus we find a simple explanation of the Fraunhofer lines. Thousands of these lines observed in such a map as that of Professor Rowland coincide exactly in position with the bright lines observed in the spectra of many elements, and we can not doubt that these elements are present in the solar atmosphere. In fact, during a total eclipse the "reversing layer," the relatively cold upper atmosphere of the Sun, emits bright lines corresponding exactly in position with the dark lines due to their absorption of the radiation coming from the hotter part of the Sun below them when the latter is not obscured by the Moon. Fig. 2, Plate IX, shows the spectrum of hydrogen made luminous by an electric discharge directly under the solar spectrum. The strongest hydrogen lines correspond in position with dark lines of the solar spectrum. In Fig. 3, the lower spectrum is that of the spark between iron electrodes moistened with a solution of calcium chloride. Many of the iron lines correspond in position with dark lines and the two intense lines marked *Ca* have the same positions as the two very broad Fraunhofer lines marked *H* and *K*.

When the photographs of a number of typical spectra are thrown on the screen you will observe not only that the spectra of different elements are unlike, but that there are marked differences in the spectra of a given element caused by changes in the physical conditions, such as the density of the vapor, the intensity of the electrical discharge, or the temperature. Some lines are intense and broad in one case, and in another narrow or altogether missing, or new lines may appear. Fig. 4 shows a part of the arc spectrum of barium, the upper with a small quantity in the arc, the lower with a larger quantity. In the second case the lines are stronger, and some new lines appear. The very intense line near the center is very much broadened and in both spectra it shows the phenomenon known as self reversal. The colder vapor around the arc absorbs light of the same wave-length as it would emit, causing a dark line across the center of the bright line. Furthermore, as shown by Fig. 5, which represents a part of the spectrum of the luminous vapors in the arc, not all spectra are composed of widely separated lines. In this case we see a large number of fine lines, arranged with a periodic regularity very close to each other, these orderly arrangements repeating themselves in separate groups. Such spectra are called band spectra. The spectra of all compounds, and also of all elements when the electric discharge is not sufficiently intense to dissociate the molecules into atoms, are composed of bands, hence we may assume that band spectra are due to the molecular state; and the evidence is equally strong that line spectra are due to dissociated and electrically charged atoms. Fig. 6 (a) shows the band spectrum of nitrogen thru which a weak electric discharge passes. The spectrograph was not sufficiently powerful to separate the many fine lines of which these bands are composed. The spectrum (b) below is that of the same gas when a more intense electric discharge passed thru it. The latter is a typical line spectrum.

It is evident from these facts that observations of the spectra of the heavenly bodies may give us much information regarding not only their chemical constitution, but also their physical state, for example their temperature, the density of their atmospheres, and even their magnetic state. If the substance of a star is dense like that of our Sun it will emit a continuous spectrum, and the hot vapors in its atmosphere will cause dark lines by absorption. If it is white hot, all colors will be emitted. If it has cooled down to red heat, its spectrum will be confined to the red. If it is still in a gaseous state, like the nebulae, the spectrum will consist of bright lines.

One of the most remarkable astronomical applications of the spectroscope is to the determination of the velocity of stars in the line of sight with respect to the Earth. The distances of all the stars are so great that it is impossible to determine their angular velocities at right angles to the line of sight except from a series of observations extending over many years. The spectroscope enables us to determine the velocity in the line of sight from a single photograph and down to a fraction of a mile per second. Here again an acoustical analogy will afford an explanation of the method. If this tuning fork is set into vibration its pitch will remain constant as long as the fork is at rest. When it is moved rapidly toward you a rise in pitch is easily observed, and a corresponding lowering of pitch when it is moved away from you. The fork starts a sound wave from its first position. If it moves forward during one vibration it will start the next wave a little in advance of its previous position. In other words, the wave has been shortened so that more waves will reach the ear in one second than if the fork had remained at rest. If the fork moves away from you the waves will be stretched out and fewer of them will reach you. This effect, known as Doppler's principle, applies also to light waves. If a star is approaching the Earth, the wave-length of a given line will be diminished and it will be slightly shifted toward the violet, and toward the red if the star is receding. The spectrum of a terrestrial source containing lines which appear in the spectrum of a star, say the hydrogen lines, is photographed alongside the spectrum of the star. The shift of the lines is then measured, and from this the velocity with respect to the Earth is easily calculated. The distance of the star in no way affects the accuracy of the result. A large part of the work of the Lick Observatory has been the determination of the velocities of a large number of stars in different parts of the sky.

These observations afford data for the determination of the velocity of the solar system itself thru our stellar universe.

What has been said will make it clear how the spectroscope enables us to extend our observations on the constitution, physical state, and velocities of the heavenly bodies thruout the enormous extent of the visible universe. Other lectures in this series will deal more specifically with some of these achievements. Let us now turn our attention to the opposite extreme, to the study of the structure and activities of the infinitesimal atoms of matter which are the ultimate sources of light. Consideration of the origin of musical sounds will help us to interpret spectroscopic observations. Sound waves are emitted from vibrating musical instruments, are transmitted thru the air, andfinally set up sympathetic vibrations in the ear which give rise to the sensation of sound. Similarly light waves originate from the vibrations within the atoms or molecules of the source. A tuning fork emits sounds of one definite pitch. This corresponds to an atom which has a spectrum consisting of only one line. As a matter of fact, no element gives such a simple spectrum except under conditions of very feeble excitation. If all the keys of a piano are struck simultaneously, a complex of sounds will be emitted, consisting of a number of fundamental tones and their harmonics. This corresponds more closely to the many-line spectrum of an element, except that in the latter case the vibration frequencies have none of the simple numerical relationships to each other. Apparently an atom must be a much more complicated structure than a piano. We could not from a study of the sounds emitted by a piano arrive at any accurate notion of its mechanical structure, and it may be imagined that the problem must be infinitely more difficult when we have to deal with an atom such as that of iron, having many thousand unrelated lines in its spectrum. Nevertheless, while we can not hope to solve the problem completely, the spectroscope, together with the study of radioactive and other phenomena, has given us a fairly definite general notion of the structure of atoms and of the way in which they emit and absorb light.

In formulating the kinetic theory of gases it was originally assumed, as a matter of convenience, that molecules and atoms are smooth, round, elastic bodies like billiard balls. This assumption will satisfy most of the needs of the kinetic theory, but it is wholly inadequate to explain the radiation of light, for it is impossible for such simple bodies to vibrate in the innumerable ways necessary for the production of a complicated spectrum. About fifty years ago Clerk Maxwell advanced the hypothesis that light waves are electrical in character. The later discovery by Hertz of electric waves which are identical in all respects except length with light waves confirmed this hypothesis. Electrical waves are set up by the vibrations of electric charges between electrodes, so we may infer that light waves are set up by displacements of electric charges in atoms. There was no way in which this process could be pictured until Zeeman made a remarkable discovery in 1896. He found that if a flame colored with sodium is placed between the poles of a powerful magnet each single spectrum line is split into two when the source is viewed in the direction of the magnetic force, and into three when viewed transversely. Fig. 7, copied from a Mount Wilson Observatory publication, shows the separation of two iron lines by the magnetic field. The doublet observed by Zeeman was found to be circularly polarized—that is to say, the electrical disturbance takes place in circular paths, propagated thru space like a vortex. The lines of the triplet were found to be plane polarized, that is to say the vibrations were in one plane, like those of a piano wire. These effects are in complete accord with a theory advanced by H. A. Lorentz, who assumed that radiation is due to the revolution of electrified particles around a central nucleus, as the planets rotate around the Sun. Electrified particles rotating in orbits parallel to the magnetic force will not have their periods of rotation changed. Those rotating in orbits perpendicular to the field will have their periods accelerated or retarded by the magnetic force according to the direction of their motion. This gives rise to two slightly separated lines when the source is looked at parallel to the field. We may imagine (if we accept the existence of an ether) that these revolving particles stir up ether vortices like those set up in a cup of coffee by stirring it with a spoon. This vortex motion propagated with the speed of light, like a rapidly revolving corkscrew in space, constitutes circularly polarized light. If we are looking at the orbits edgewise we see only the transverse components of motion, like the up and down motion of the crank pin of a fly wheel, and thus we get the three plane polarized components due to the particles which are retarded, accelerated, or not affected by the magnetic field. From a study of the direction and magnitude of the displacements of the lines it was determined that these particles are negatively charged, and that they have a mass about one eighteen-hundredth that of a hydrogen atom. They are thus found to be identical with the cathode rays, which J. J. Thomson about the same time showed to have the same charge and mass. These particles are called electrons, and play a great part in modern physics. A study of cathode rays and related phenomena shows that these electrons are constituents of all kinds of matter and under certain conditions may be readily separated from the atoms.

A study of radioactive phenomena leads to similar conclusions, and shows conclusively, moreover, that the heavier atoms, such as those of uranium, thorium, and radium, are constantly breaking down into smaller parts. The old idea of the indestructibility of the atom must therefore be revised, altho these discoveries placed the atomic theory on a firmer foundation than ever. To explain certain anomalies and energy relations the Lorentz theory of the Zeeman effect has been considerably modified, but it still leaves us the picture of the atom as a planetary system. Evidence derived from the study of radioactivity as well as of spectroscopic phenomena makes it seem highly probable that the atoms heavier than hydrogen and helium are built up in the following manner: In the center is a small but relatively heavy nucleus composed of hydrogen and helium atoms and electrons, with an excess positive charge. At distances of the order of one thousand to ten thousand times the diameter of this nucleus a number of electrons revolve in one or more orbits. The diameter of the whole system is about one three-billionth of an inch. The displacements of these negatively charged electrons from an outer to an inner orbit due to some external shock causes the emission of light waves; and light waves of the same frequency may displace an electron from an inner to an outer orbit and thus cause absorption of energy. These external electrons probably also furnish the electrical forces which hold atoms together in chemical combinations. Sometimes, in the case of the radioactive elements, internal equilibrium may be upset in some way unknown to us, resulting in an atomic explosion, so that atoms of helium (alpha particles) may be projected outwards, leaving a smaller atom behind. It has been proved that uranium disintegrates in this manner down to radium, and this in turn down to lead. What happens beyond that we do not know, but we can infer the probability of other atomic disintegrations. In fact, Rutherford has recently almost conclusively proved the possibility of breaking down nitrogen atoms into helium and hydrogen atoms by the impact of swift alpha particles.

Such is the picture of the atom revealed to us by the study of spectroscopic and radioactive phenomena. Time does not permit a detailed examination of the evidence, and many points are still unexplained; but physicists have abundant reasons for believing that the real atom can not greatly differ from the hypothetical atom described above.

We thus see that each atom is a miniature solar system. The question naturally arises—but can not now be answered—Does nature repeat itself *ad infinitum;* are there other systems smaller than those of atoms?